TOPSAR ANALYSES OF ACTIVE VOLCANOES IN THE PACIFIC

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1. INTRODUCTION

Understanding the long-term volumetric output of a volcano is valuable for constraining magma supply (e.g., Wadge, 1977; Crisp, 1984) as well as providing information about magma plumbing systems and long-term eruptive cycles (Holcomb, 1987; Dvorak and Dzurisin, 1993). A similar need also exists for documenting the erosion rates of deposits produced by explosive eruptions, because these materials are then reworked to form mudflows (called "lahars") that are deposited downslope. We have therefore been using data collected on earlier deployments of the NASA DC-8 to volcanoes in the Pacific Basin to investigate the long-term output of different volcanoes, as well as assess their hazard potential. These investigations enable us to make several recommendations for the upcoming PacRim 2000 deployment of the NASA DC-8.

We describe here our studies of TOPSAR data collected during three deployments of the NASA DC-8 to investigate the changes in morphology of active volcanoes in Hawaii (May 1993 deployment), the W. Galapagos Islands (August 1993), and Mt. Pinatubo in the Philippines (November 1996). In the past, digital topographic data have proven useful for studying the local slopes (Mouginis-Mark and Garbeil, 1993; Mouginis-Mark et al., 1996), the thickness and volume of lava flows (Rowland, 1996; MacKay et al., 1998) and the large-scale morphology of shield volcanoes (Rowland and Garbeil, in press). Here we concentrate on our recent efforts to utilize the data to study ongoing volcanic processes to (1) understand the rate of eruption of lava flows; (2) investigate the use of TOPSAR for lava flow hazard mitigation; and (3) identify the year-to-year rate of erosion of the ash deposits that formed on Mt. Pinatubo during the June 1991 eruptions.

2. VOLCANO STUDIES

2.1 Kilauea Volcano, Hawaii. Until recently, most estimates of lava flow volume have relied on measuring margin thicknesses at multiple locations along the flow edge and multiplying these by planimetric flow areas, or by time-consuming surveying campaigns (e.g., Fink and Zimbelman, 1990; Stevens et al., 1997). To explore the utility of remote sensing techniques, we have conducted a comparison between the 1993 TOPSAR data and a 1977 U.S. Geological Survey (USGS) digital elevation model (DEM) (Rowland et al., 1999). A subtraction of the two topographic data sets produced volume estimates of 392, 439 and 90 x 10^6 m^3 for the Puʻu Oʻo, Kupaianaha, and the Episode 50 – 53 stages of the eruption, respectively. Such values yield volumetric eruption rates of 4.5, 4.5 and 2.7 m^3 s^{-1}, which are similar to field estimations made by other investigators.

However, problems have been encountered in using the USGS DEM for comparison with 1993 TOPSAR data set. For instance, the USGS DEM was derived from stereo air photographs, and contains several inconsistencies in the elevation data between flight lines. Also, this DEM contains an approximation for the removal of the heights of trees, which is an attribute that cannot be removed from the C-band TOPSAR data. Thus any direct subtraction of one DEM from the other produces negative topographic changes over time in areas where there are trees. Such problems would not, of course, be relevant if two different TOPSAR passes were inter-compared. We hope that the new PacRim 2000 data for Kilauea will enable us to determine this volume and, hence, the average eruption rate.

We have also been comparing the 1993 TOPSAR data for Kilauea with DEMs derived from interferometric processing of ERS-2 orbital radar images collected at the University of Hawaii's X-band ground station by Torben Nielsen and his group. Because the Puʻu Oʻo vent has been nearly continuously active since 1993, we expect that a considerable volume of new lava flows has been created. Using both sets of supplemental digital elevation data, we have been able to produce maps of volume change on the active lava flow field.

In the case of the TOPSAR vs. ERS-2 DEMs, other issues become important. Warping of the 1993 TOPSAR data has made it difficult to perform exact elevation comparisons over small areas because the much of the recent activity has been tube-fed flows. Also, although there are three different ERS-2 orbits that image Kilauea every 35 days (the repeat cycle of the spacecraft), the baseline separation of the orbital pairs is often inappropriate for long-term comparisons. To date, we have been able to generate ERS-2 DEMs for late 1998, and for June/July 1999. Comparisons of these DEMs are currently underway as they offer a new opportunity to compare the volume eruption rate of the volcano over the last year, and to calculate the total volume of lava erupted since the last TOPSAR data set was collected in 1993.

2.2 W. Galapagos Islands. One of the first large-area TOPSAR DEM mosaics that JPL produced was of the western Galapagos Islands. These data were collected in May 1993 in support of the Space Shuttle Radar (SIR-C/X-SAR) missions in 1994. Since that time, we have been using these TOPSAR data for detailed studies of the six active volcanoes, with special attention given to Fernandina and Cerro Azul volcanoes.

In particular, these TOPSAR data have presented unique opportunities for studying the most recent eruptions. New lava flows formed on Fernandina in January 1995, and Cerro Azul erupted in September 1998. The TOPSAR data permit analysis of the deformation of the volcanoes due to the intrusion of a dike on Fernandina (Jonsson et al., 1999), as well as investigate the effects of pre-existing topography on the flow path of an active lava flow. In this latter case, we are only just now starting an investigation that compares the three-dimensional shape and flow path of the Cerro Azul lava flow, but we will report on our preliminary observations. This eruption was an unusually good one for the study of lava flow dynamics because the 16 km long flow we observed the flow almost hourly using thermal infrared data obtained from the geostationary GOES weather satellite, and our collaborators at the Charles Darwin Research Station in the Galapagos made several measurements of flow rate and lava flow thickness (Mouginis-Mark et al., in press). Temporal variations in flow rate and flow geometry may therefore be compared to numerical predications of the flow path based on the pre-existing slope characteristics of the volcano.

This study may also have broader applications for the use of TOPSAR data obtained over other volcanoes. For example, the summit of Mauna Loa volcano in Hawaii was imaged by TOPSAR during the August 1996 deployment. Although Mauna Loa has not erupted since 1984 (Lockwood and Lipman, 1987), a new eruption has been expected here for a number of years, and new activity might well occur within the next 5 – 10 years. When Mauna Loa does erupt, it is expected that great interest will be generated regarding the likely flow path(s) of the lava flows because of their potential threat to recently developed areas; additional development has taken place in parts of the town of Hilo to the NE of the volcano, and comparable development has taken place on the western flanks in Kailua-Kona. If the utility of the TOPSAR data is known in advance from our studies of the 1998 Cerro Azul lava flow, then it should be possible for TOPSAR data for Mauna Loa to be used in numerical models that predict the flow-path of lava flows. Indeed, one such study is just being started in support of the Pacific Disaster Center in Maui, so that our Galapagos investigation may be very timely.

2.3 Mt. Pinatubo, Philippines. This volcano was one of the areas imaged during the PacRim I deployment in November 1996. As with the experiment for Kilauea volcano, we wish to repeat the same TOPSAR coverage of Mt. Pinatubo in order to study the changes in topography that have taken place due to the erosion of the pyroclastic flows, and their re-deposition as a series of lahars. Until the advent of high-resolution digital topography, it has been very difficult to document post-depositional volcanic processes over the huge area (~2000 km^2) of affected rough and inaccessible terrain. Not only are the geomorphic processes complex, but also it has often been dangerous to work in the field when heavy rains form new lahars (Torres et al., 1996). During PacRim 2000, we propose to collect a second TOPSAR DEM for the western pyroclastic fan, the summit area, and the Pasig-Potrero River in order to quantify these topographic changes. These data will enable us to derive a better estimate of the erosion/deposition of materials on the volcano (i.e., determine the "sediment budget" for the volcano).

In 1998, there were two particularly severe episodes of erosion on the volcano due to the passage of Typhoons Zeb and Babs. These lahars drastically modify valley topography near the summit of Mt. Pinatubo, which in turn modifies the extent and direction of future lahars. Erosion and gullying during torrential rain is a significant aspect of lahar generation on the volcano (Torres et al., 1996). Deposits up to several meters thick can be rapidly formed in one event (e.g., up to 6 m of aggradation in the Pasig-Potrero system in one 14-hour period in October 1995). Down cutting can be equally rapid (e.g., a 30 m deep channel formed in November 1995 following Typhoon Rosing). We are therefore confident that there will be major changes in the topography of the volcano flanks that can be measured via a direct comparison of the PacRim I and PacRim 2000 TOPSAR data sets.

This continuing study of Mt. Pinatubo will be done in collaboration with Filipino volcanologists at PHIVOLCS, under funding provided by NASA's Natural Hazard Program. Currently, we are striving to identify new collaborators in Manila, following staff changes at the Institute. In the interim, we will work with Ronnie Torres, who is working at PHIVOLCS. Our intent is to continue our collaborations with the Filipino investigators as part of PacRim 2000.

3. PACRIM 2000 RELATIONSHIPS TO OTHER NASA MISSIONS

A further issue is the potential for TOPSAR data to be used as a comparative data set for the up-coming flight of the Shuttle Radar Topographic Mission (SRTM), currently scheduled for launch in September 1999. SRTM will collect a digital topographic map of the globe between 60°N and 57°S. While the spatial resolution of these data will be 25 m/pixel at best, we have seen from our comparative studies of the TOPSAR and DEM's derived from interferometric processing of ERS-2 radar data that this resolution difference does not preclude useful volcanological studies.

TOPSAR data could become one of the primary methods for the validation of SRTM data, as well as measurements made by another NASA topographic mapping mission called the Vegetation Canopy Lidar (VCL) which will fly in 2001. We plan to use TOPSAR and a commercial interferometric radar system called Star-3i to validate SRTM data for four sites: Kilauea (Hawaii), Mt. Pinatubo (Philippines), Cerro Azul and Fernandina volcanoes (Galapagos Islands), and Tengger caldera (Java). The Star-3i system is particularly interesting because in addition to the 10 m/pixel DEM, there is also a 2.5 m/pixel radar backscatter image (collected at X-band). We hope to perform an inter-comparison of VCL and SRTM data over these sites, and use VCL data to remove tree heights from SRTM topographic measurements to generate "bald Earth" DEMs for the volcanoes of interest. Knowledge of the instrument performance will enable the mission Science Teams to better evaluate the influence of tropical vegetation when other portions of the SRTM and VCL data sets are studied.

A further interesting study that we plan to coordinate with Luke Flynn and Andy Harris at the University of Hawaii is the estimation of magma production rates from observations made by the GOES-10, Landsat 7 and the Terra spacecraft. For example, Harris et al. (1998) have already shown that the total mass of lava can be estimated from thermal infrared observations of volcanoes. In the case of Kilauea, we therefore have the opportunity to inter-compare the topographic estimates of lava volume with this independent estimate of magma flux based on the thermal data.

4. RECOMMENDATIONS FOR PACRIM 2000

Our work with the TOPSAR data collected in 1993 and 1996 shows that care needs to be taken when planning future deployments of the system if the maximum potential of the data is to be achieved. What we have seen in our earlier studies of the TOPSAR data is the need for temporal coverage of the sites. Flight lines need to be selected so that they replicate the earlier observations as closely as possible. This will facilitate co-registration of the observations, as well as ensure that the maximum area can be inter-compared. Look-directions should also be the same, so that data loss due to radar-shadowing is replicated between data sets. Radar-shadows are, for example, a particular problem on the upper slopes of Mt. Pinatubo due to the high near-vertical walls of the eroded river canyons.

We believe that one of the greatest contributions that we can make via these studies is an estimation of the rate of change on the volcano. This could take the form of calculating the volume of new lava flows erupted on Kilauea volcano, or the analysis of the rate of erosion of lahars on Mt. Pinatubo. In both cases, the main benefit of the TOPSAR acquisition comes when there are two (or more) similar data sets collected over the same target several months or years apart. The volcanic processes do not, in general, happen overnight, and so it is unlikely that significant changes could be observed via repeat coverage during one site visit during PacRim 2000. An exception might be to collect data over the lava flow field at Kilauea during the western transit to the DC's western Pacific, and then to again collect data during the return to the U.S. mainland several weeks later. However, the success of this experiment would depend on the detailed eruption characteristics of the volcano, which in recent years has sent most of the new lava volume directly to the coast via a series of lava tubes, thereby preventing the development of new surface lava flows.

The lava flow field of the Pu‘u O‘o vent of Kilauea Volcano has the highest priority of any of the targets in the PacRim 2000 data request. Our primary goal is to collect new TOPSAR data over the lava flow field in order to make a volume comparison with the 1993 TOPSAR measurements. This will enable us to better understand the long-term (7-year) volumetric output of the volcano, which is in turn important for constraining magma supply. Intermediate values may also be derived via comparison with the ERS-2 DEM's.

Our second priority is the analysis of the changes in the pyroclastic flows and lahars at Mt. Pinatubo, Philippines. During the PacRim I deployment in 1996, two TOPSAR data takes were collected over the central portion of the volcano and we hope that these flight lines will be replicated in 2000. There are two areas where we have greatest interest in measuring the volume change on Mt. Pinatubo: 1) analysis of the degree of incision on the western pyroclastic fan (just west of the summit) and the upper reaches of the Pasig-Potrero River system will enable us to evaluate the amount new material that has been mobilized during tropical storms; and 2) analysis of the new lahar (mudflow) fans produced at the lower reaches of the Pasig-Potrero River will permit the "sediment budget" of the volcano to be estimated. This is particularly important since mudflows are still being generated on the volcano, and so continue to pose a threat to the local population that has now moved back into the area following the 1991 eruptions.

Our third priority is baseline topographic mapping American Samoa with TOPSAR. Here we wish to explore the morphology and geology of this infrequently studied volcanic island that shows many of the same rift zones features that we can observe on Hawaiian volcanoes. We also hope that MASTER data can be collected at Kilauea and White Island, which will enable us to study temporal changes in the gas flux of these volcanoes. These gas studies would be done in collaboration with Vince Realmuto at the Jet Propulsion Laboratory, CA, who is a member of the NASA EOS Volcanology Interdisciplinary Science Team.

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